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Effect of wind energy system performance on optimal renewable energy model—an analysis

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Abstract

The Optimal Renewable Energy Model (OREM) has been developed to determine the optimum level of renewable energy sources utilisation in India for the year 2020–21. The model aims at minimising cost/efficiency ratio and determines the optimum allocation of different renewable energy sources for various end-uses. The extent of social acceptance level, potential limit, demand and reliability will decide the renewable energy distribution pattern and are hence used as constraints in the model. In this paper, the performance and reliability of wind energy system and its effects on OREM model has been analysed. The demonstration windfarm (4 MW) which is situated in Muppandal, a village in the southern part of India, has been selected for the study. The windfarm has 20 wind turbine machines of 200 KW capacity. The average technical availability, real availability and capacity factor have been analysed from 1991 to 1995 and they are found to be 94.1%, 76.4% and 25.5% respectively. The reliability factor of wind energy system is found to be 0.5 at 10,000 hours. The OREM model is analysed considering the above said factors for wind energy system, solar energy system and biomass energy systems. The model selects wind energy for pumping end-use to an extent of 0.3153×10^{15} KJ.

1. Introduction

The conventional coal and oil fired power plants and wood/crop residues cause environmental problems such as land degradation, water and air pollution. Global warming and acid rain are attributed to carbon-dioxide, sulphur-dioxide and oxides of nitrogen emissions from fossil fuel burning in power plants. Hence a nation

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must look into other energy options such as wind and solar energy, to overcome environmental problems. Energy from wind and the sun are found to be the most promising among non-fossil fuel sources. Biogas releases carbon-dioxide, although it is otherwise thought to be a clean source. Nuclear power does not emit particulate or gaseous pollutants, but the reactors discharge a dilute radioactive liquid effluent.

It is obvious that the environmental benefit of wind energy ranks very high among the renewable energy sources. It has been estimated that one 500 KW wind turbine at a good wind site in one year avoids the generation of 1.1 million kilograms of carbon dioxide, 8200 kg of slag and fly ash, 9000 kg of sulphur dioxide and 7000 kg of nitrogen oxides [1]. Wind energy is abundantly available and is also the cheapest source for generating power. The capital cost for wind energy projects ranges between Rs. 3.50–4.00 crores/MW while the cost of generation varies from Rs. 1.75–2.25 KWhr [2]. The wind power cost is expected to further decline through technical advancements in wind machines, cost-cutting improvements in manufacturing techniques and environmental concerns. Hence it is a proven factor that wind energy is cost effective and environmentally benign. In this paper, an attempt has been made to analyse the other key factors like capacity factor and reliability factor of wind energy system and its effect on OREM model.

2. Energy models

Modelling has been initiated in recent years for effective utilisation of renewable energy sources since it is taking place in an unplanned, uncontrolled and inefficient manner. A nonlocational model was developed by Satsangi and Sarma [3] which considers the national energy system in its totality with particular reference to choices for renewable energy sources. The model considers energy supplies from the traditional and nontraditional sources and also permits evaluation of renewable energy technologies. Gwo-Hshiung Tzeng et al. [4] has developed a multicriteria evaluation method to evaluate comprehensively the alternatives for new energy-system development. Energy technology, environmental impacts and economic factors were evaluated and development directions and strategy for future energy systems in Taiwan are proposed. The optimization model is applied by Barry Hyman et al. [5] to the particular problem of meeting the projected generation requirements in Washington State during the year 2000. Analysis is performed to determine the optimum combination of five new technologies (wind, photovoltaics, small hydro, cogeneration, and biomass) as additions to the existing hydrothermal system. Kamal Rijal et al. [6] described the methodology adopted to arrive at a casual linear multiple regression to estimate and project end-use energy requirements of a rural household of Nepal. A general linear programming model is developed by Jyoti Parikh [7] to capture energy and agricultural interactions existing in the rural areas of developing countries. The model is applicable to low-income, biomass-scarce developing countries. Das T.K. et al. [8] dealt with selecting appropriate alternate energy technologies with priorities to end-use activities in the agriculture and household sectors by the use of dynamic programming. Modified and Mathematical programming energy economy environ-

ment models have been developed by Suganthi L. and Jagadeesan T.R. [9] to predict the commercial energy requirements in India. Economic factor, environmental factor and technological factor have so far been considered in the renewable energy optimisation models. It is realised that reliability factor and social acceptance factor have to be considered for realistic predictions and they are incorporated in the Optimal Renewable Energy Model developed in the present work.

3. Optimal Renewable Energy Model (OREM)

The various renewable energy options for different end-uses such as lighting, cooking, pumping, heating, cooling and transportation are shown in Fig. 1. The details are given as follows: The pumping end-use can be met by solar thermal pump, solar PV pump, solar thermal electric conversion, wind energy system, biomass gasifier engine, biogas fueled engine and ethanol fueled engine; the cooking end-use can be met by solar thermal-solar cooker, solar PV electric conversion, solar thermal electric conversion, wind energy electric conversion, biomass direct combustion, biomass gasification and biogas; the transportation end-use can be met by solar PV electric conversion, solar thermal electric conversion, wind energy electric conversion, biomass gasifier engine, biogas fueled engine, ethanol fueled engine; the lighting end-use can be met by solar PV electric conversion, solar thermal electric conversion, wind energy electric conversion, biomass electric conversion and biogas electric conversion; the cooling end-use can be met by solar thermal (absorption system), solar PV electric conversion, solar thermal electric conversion, wind energy electric conversion, biomass electric conversion, and biogas electric conversion system; the heating end-use can be met by solar thermal, solar PV electric conversion, solar thermal electric conversion, wind energy electric conversion, biomass direct combustion, biomass gasification and biogas system.

The schematic representation of the Optimal Renewable Energy Model (OREM) is shown in Fig. 2. A Delphi study has been conducted to find out the social acceptance in the utilisation of renewable energy sources. The participants in the Delphi study were Policy makers, Scientists, Academicians, Agriculturists, Manufacturers and users of renewable energy systems in industrial, transportation, agricultural and domestic sectors. Three hundred energy experts participated in the Delphi study. The study revealed that cost and efficiency are the important factors in the utilisation of renewable energy sources. In the OREM model minimisation of cost/efficiency ratio has been chosen as the objective function. The experts considered other factors also such as technology, availability and reliability while selecting the appropriate renewable energy systems for different end-uses.

The percentage utilisation of renewable energy sources for different end-uses was obtained from Delphi analysis. The two stage least square forecasting method is used to predict the energy demand for the year 2020–21. The social acceptance factor for renewable energy sources was obtained from Delphi and was used as a constraint in the model. The predicted energy demand is compared against the social acceptance level and the optimum renewable demand for different end-uses was determined.

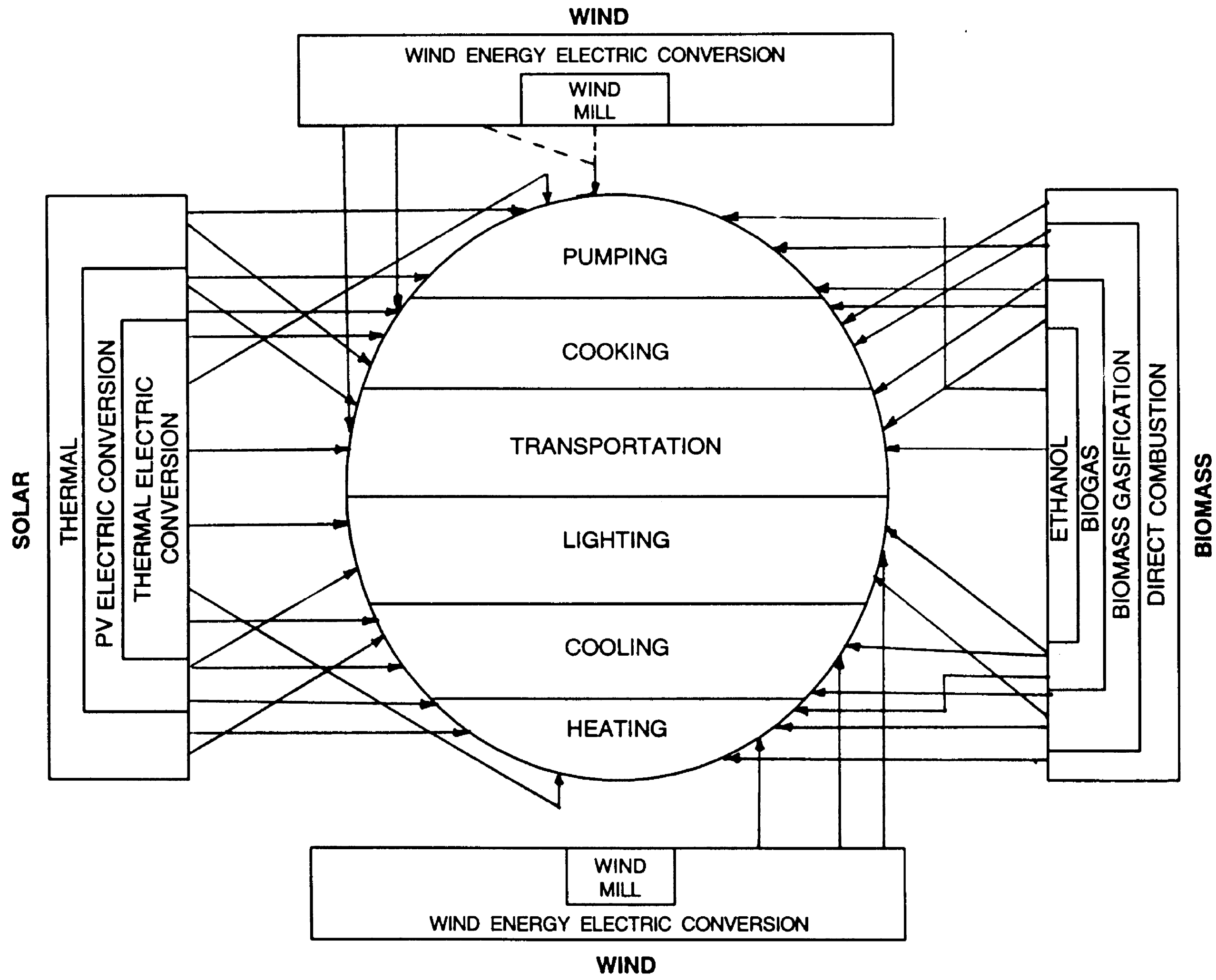

Fig. 1. Schematic representation of renewable energy options for different end-uses.

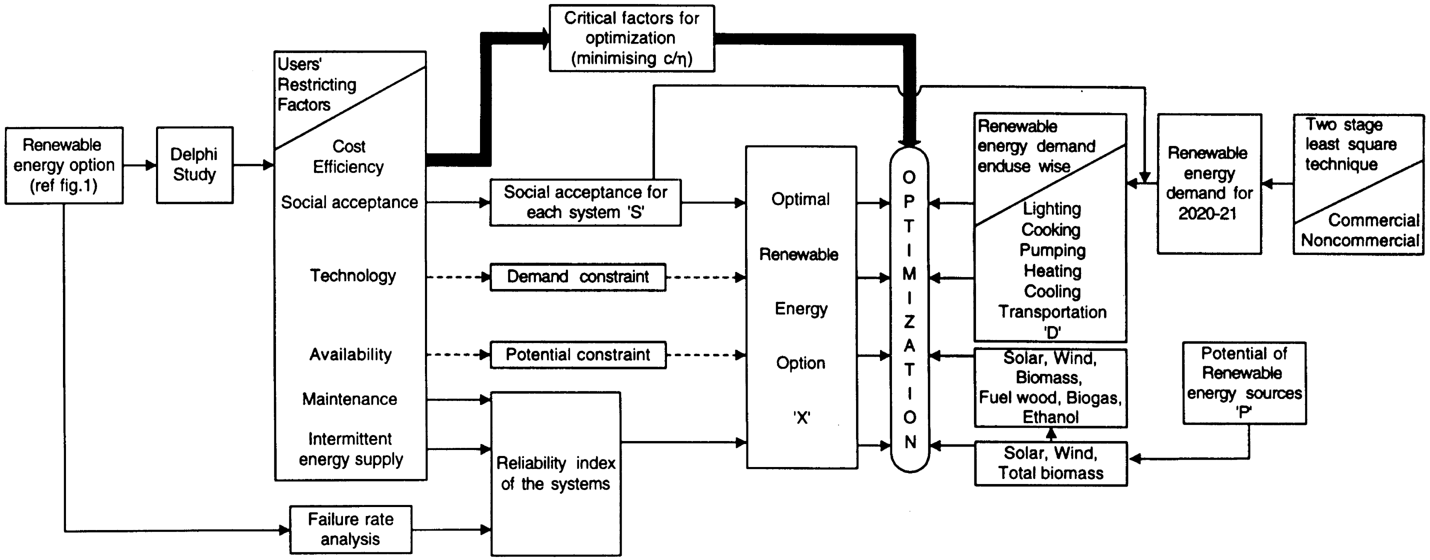

Fig. 2. Schematic representation of optimal renewable energy model (OREM).

The demand for the different end-uses as a percentage to total energy demand is predicted and used as an end-use constraint in the model. Even though abundant potential of solar, wind and biomass energy is available in India, the factors like quality of the resources, intermittent nature and technical feasibility will decide the quantum of energy utilisation from different renewable energy sources. In the OREM model this is considered as a resource constraint.

The reliability of different renewable energy systems has been studied. The Mean Time Between Failures (MTBF) was calculated from the maintenance records in order to analyse the reliability factor of the system. The calculated reliability index for the renewable energy systems is used to formulate the constraint equation. The source wise potential is used in this equation.

The OREM model optimises the values in the utilisation of renewable energy options for the year 2020–21 based on cost, efficiency, social acceptance, potentials and reliability of the system. This will be a better suited model for policy makers.

3.1. *Mathematical representation*

$$\text{Minimise} \sum_{j=1}^{6} \sum_{i=1}^{l} (C_{ij}/\eta_{ij}) X_{ij}$$

subject to

$$\text{Social acceptance} \sum_{j=1}^{6} \left[\sum_{i=1}^{l} (X_{ij}/S_{ij}) \leqslant D_j \right]$$

$$\text{Potential limit} \sum_{k=1}^{6} \left[\sum_{i=1}^{m} (X_{ik}) \leqslant P_k \right]$$

$$\text{Demand} \sum_{j=1}^{6} \left[\sum_{i=1}^{l} (X_{ij}) \leqslant D_j \right]$$

$$\text{Reliability} \sum_{k=1}^{3} \left[(1/R_k) \sum_{i=1}^{m} (X_{ik}) \leqslant P_k \right]$$

where

η = Efficiency of the system
C = Cost of the system
D = Demand
P = Potential limit
R = Reliability Index
S = Social acceptance
i = renewable energy system
j = end use
k = resource
l = number of systems in respective end-use

$l = 5$ for lighting
$l = 7$ for cooking
$l = 7$ for pumping
$l = 6$ for heating
$l = 6$ for cooling
$l = 7$ for transport
m = number of systems in respective resource
$m = 16$ for solar
$m = 6$ for wind
$m = 6$ for biomass
$m = 2$ for fuelwood
$m = 6$ for biogas
$m = 2$ for ethanol

The paper highlights the method used to find the reliability factor of one renewable energy system (i.e.) wind energy system as an example. For this purpose, the 200 KW wind energy system situated at Muppandal in the southern part of India is considered. The performance and reliability of the wind energy system from 1991 to 1995 has been analysed in the following sections to arrive at a reliability factor. The reliability index of solar energy system and biomass energy system is also arrived from the previous study [10, 11].

4. Performance of wind energy system

4.1. *Availability analysis*

Future growth of windfarms in India is likely to be based on systematic availability and reliability studies. Such an exercise will not only enable well informed decisions to be taken but also help in developing reliable hardware. Some of the issues involved are presented and discussed in the following sections.

4.2. *Technical availability*

The technical availability is the fraction of time in a year that the wind turbine is potentially able to generate electricity. A wind turbine can be unavailable because of planned maintenance activities or because of the unforeseen failures, incidents or accidents. The technical availability of the wind turbine generators has been analysed for each month from the year 1991 to 1995. The technical availability is the ratio of Operation hours to Total machine hours available in the month.

The technical availability levels of the Muppandal windfarm are shown in Fig. 3. It reveals that the technical availability was steady and it was more than 95% from the year 1991 to 1994. Because of the frequent grid faults the technical availability was fluctuating during the year 1995. The trouble free wind turbine generators will have the maximum of 100% technical availability. By minimizing the grid down

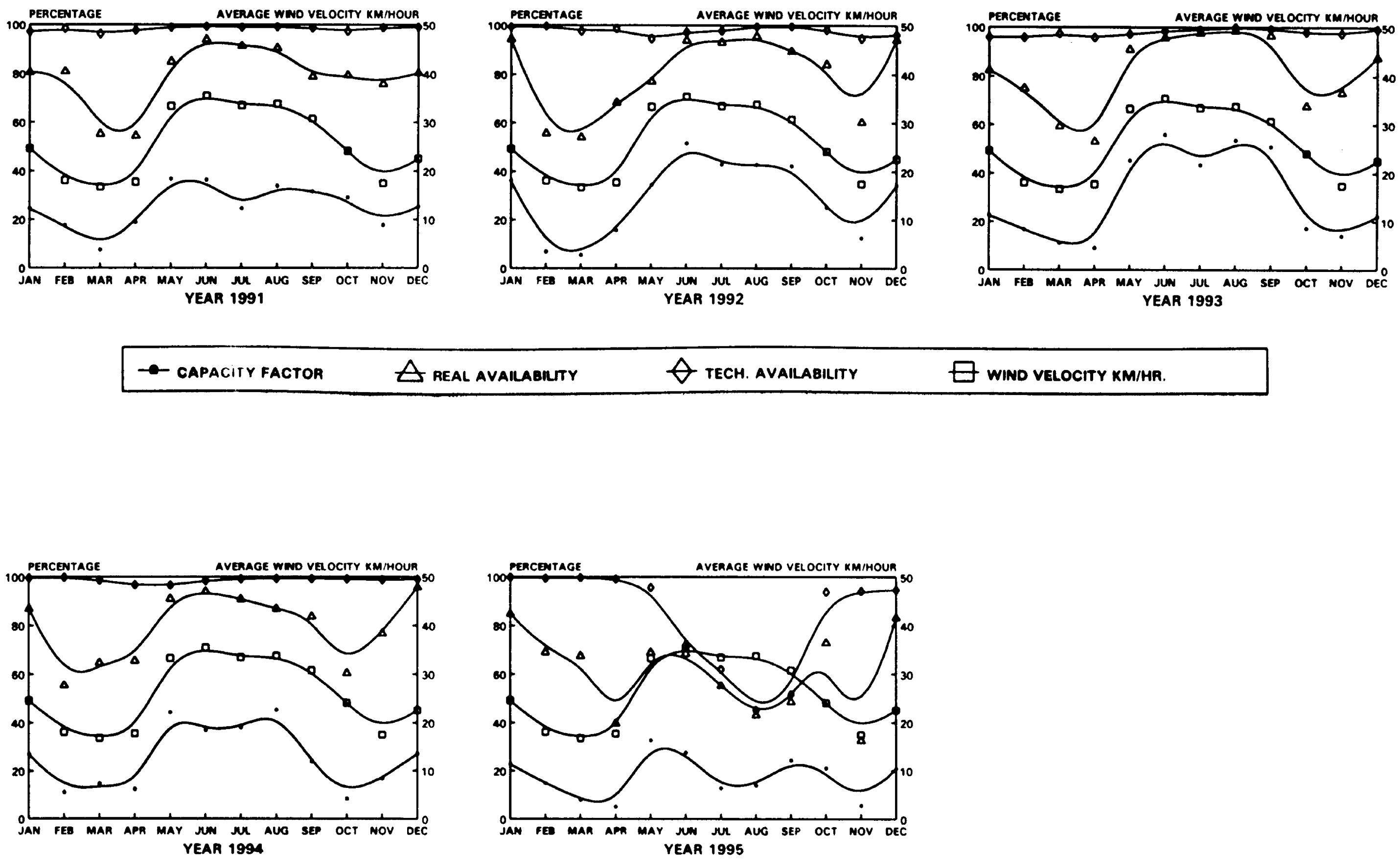

Fig. 3. Performance characteristics of Muppandal windfarm.

time and machine down time the technical availability of the windfarm can still be increased.

4.3. *Real availability*

The real availability is the net availability after exclusion of machine fault and maintenance hours, grid fault and maintenance hours and low wind speed hours. The real availability is the ratio of Generation hours to Total machine hours.

The wind velocity and real availability from the year 1991 to 1995 are also shown in Fig. 3. From June to August the wind velocity is above 33 km/h in Muppandal area. In this period the machine hours lost due to inadequate wind speed were less and the real availability was more than 85% except in the year 1995. In the month of February, March, April and November the wind velocity was less than 20 km/h which results in lower real availability. The real availability can be improved by reducing machine and grid failure hours. Since the real availability mainly depends upon the wind speed, the performance gets improved with the higher wind speed.

4.4. *Capacity factor*

The capacity factor has been calculated for the wind turbine generators over the years which is the ratio of Actual generation to Installed capacity.

The capacity factors of the wind farm from the year 1991 to 1995 is depicted in Fig. 3. The capacity factor reaches a peak value of more than 50% in the month of June '92 and June '93 and this is due to high wind velocity of 35 km/h. Since the wind velocity is less in the months of February, March, April and November the capacity factor was less than 20%. This indicates that the capacity factor is highly dependent on wind velocity.

4.5. *Percentage distribution of total availability*

The total availability is the combination of real availability and various losses. The percentage of real availability and availability loss due to low wind speed, machine fault, machine maintenance, grid fault and grid maintenance are shown in Fig. 4 for the period 1991 to 1995. During the year 1991, the real availability and availability loss due to low wind speed are 78.97% and 19.25% respectively. The availability loss due to machine fault, machine maintenance, grid fault and grid maintenance are 0.3%, 0.47%, 0.55% and 0.46% respectively, and the combined value is 1.78% (Fig. 4). Almost similar trend was continued during the year 1992, 1993 and 1994 and this is also represented in Fig. 4. The machine faults and grid faults can be minimized by improving operation and maintenance schemes. During the year 1995, the real availability has a comparatively less value of 61.34% due to more grid downtime of 13.04%. The wind turbine system will be unavailable because of power failure in the grid. Induction generators used in windfarms draw considerable reactive power from the grid while supplying the active power. The reactive power is required to magnetize the induction generator for its operation. By maintaining a continuous power supply,

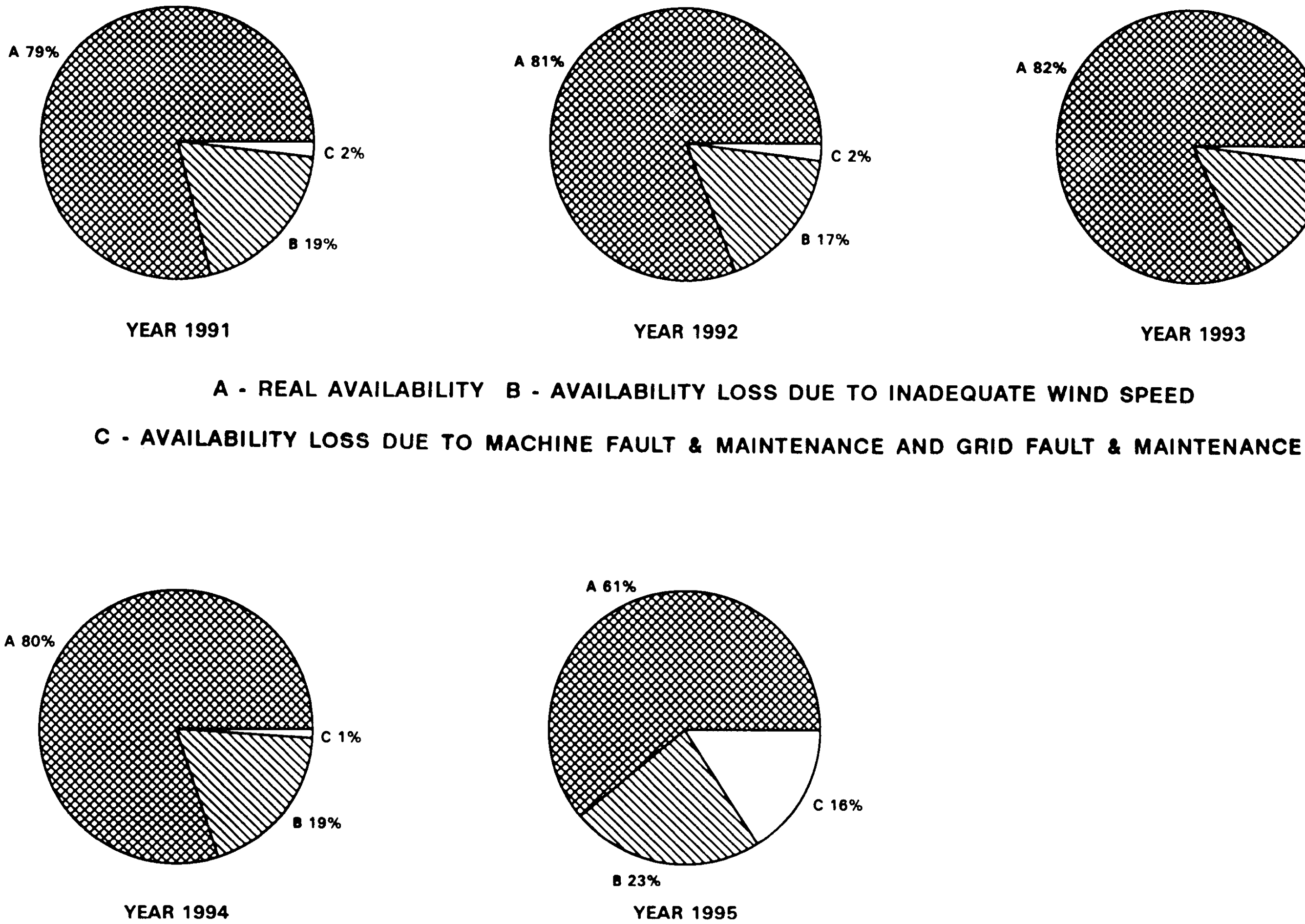

Fig. 4. Percentage distribution of total availability.

down time in the grid can be eliminated which will result in an increase in real availability. The fault analysis has been done to identify the adverse technical problems in the grid.

4.6. *Analysis of grid related problems*

Large wind turbines connected to the grid commonly use induction machines that operate as generators running at higher than their synchronous speeds. The same machines are also used to start the wind turbine by running as induction motors, drawing power for this function from the grid.

Figure 5 shows the Pareto diagram which represents the frequency of different faults which occurred in the wind turbine generators. There are five faults identified. They are grid drop, frequency fault, asymmetric current, over voltage and under voltage. The Pareto analysis reveals that if over voltage and under voltage problems are removed completely then the overall reduction in the frequency of faults is only 8.6%. On the other hand if only 50% of the failures due to frequency fault and asymmetric current are removed, then it will result in 12.8% reduction in overall failure. Instead, if 50% of failures due to grid drop alone is tackled, then the overall reduction in the frequency of faults will be 33.1% which is significant. The following steps have been suggested to tackle the grid faults.

Since greater numbers of wind turbine generators are being installed in one location, the requirement of the reactive power is very high and it causes low voltage problems. Shunt capacitors can be installed in the windfarm sub stations to overcome these problems. During night hours, over voltage problems may arise and this can be avoided by installing OLT (On Load Tap) changer in the transformer. The grid is connected to the southern states and power houses such as Kalpakkam, Neyveli and Ramakundam in the country. It has been found that the grid frequency is always below 50 Hz because of deficit in power generation in all the states. But wind turbines are designed to give the rated output at 50 Hz. Since the rotor speed is low during low frequency hours, the output goes down below the designed value. Hence steps should be taken to maintain the frequency at the rated value. It is also suggested that the blade profile can be modified suitable to make the output not vulnerable to minor variation in speed.

The output of the wind turbine is very much dependent upon the air density. Manufacturers assume an air density of 1.23 Kg/m^3 while they design the wind turbine. But the average air density has been found to be only 1.1 Kg/m^3 in India. Because of the variations in air density the output of the wind energy generator reaches 90% of the capacity at rated wind speed. Hence the wind turbines are to be designed to the conditions prevailing in India so as to economise the other grid interfacing equipment.

5. Reliability of wind turbine generator

Reliability is the probability that a device will operate without failure for a given period of time under given operating conditions. An evaluation of system reliability

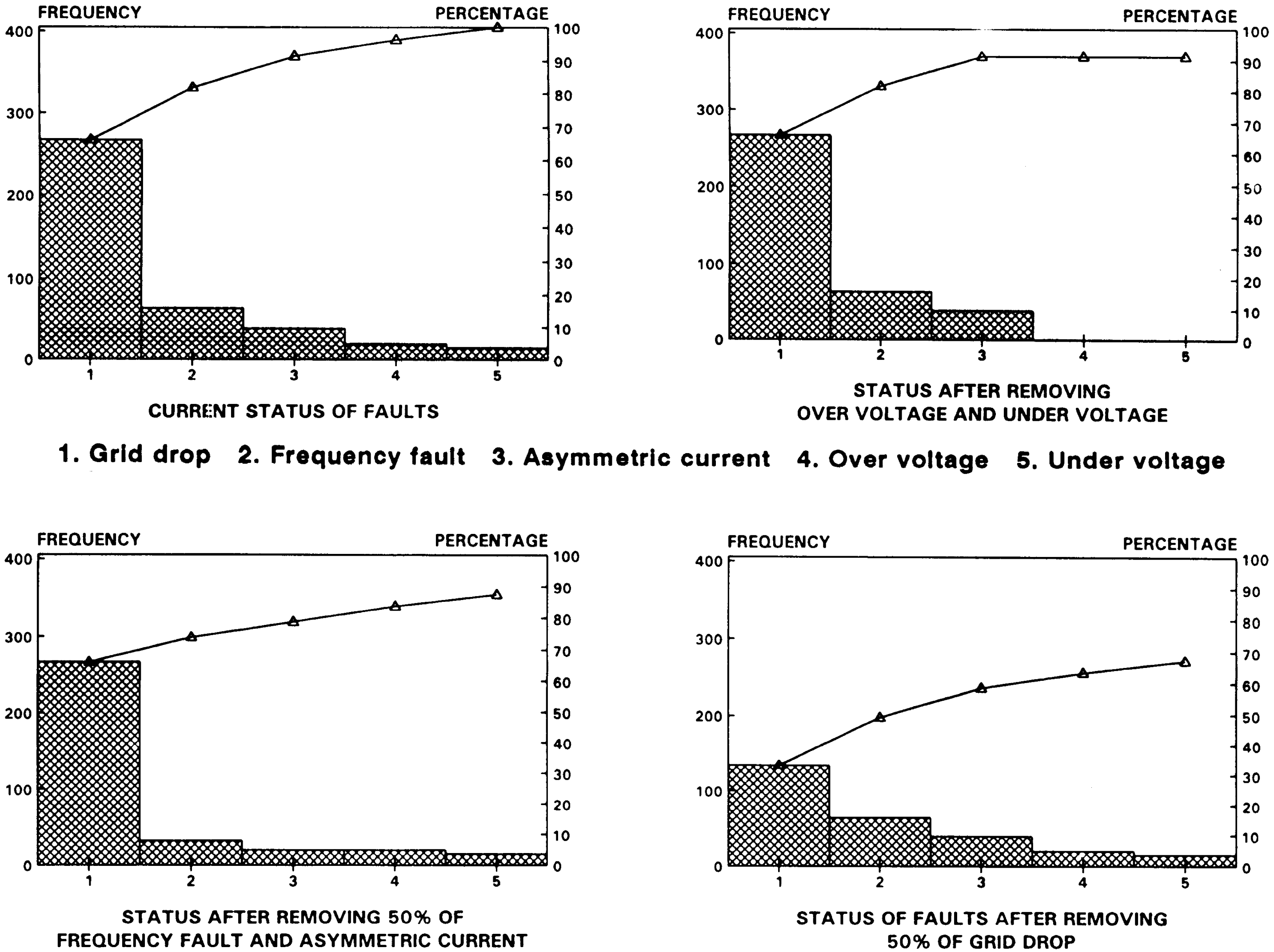

Fig. 5. Pareto diagram for grid fault analysis.

becomes essential to decide whether a system will accomplish its mission successfully. The prediction of system reliability is based on life characteristics. The life length can be measured by Mean Time Between Failures (MTBF). During the operating period, when failure rate (λ) is fairly constant, the Mean Time Between Failures (MTBF) is the reciprocal of the constant failure rate [12].

$$\mathrm{MTBF} = \frac{1}{\lambda}$$

Mean Time Between Failures is also referred to as the average time of satisfactory operation of the system. In this case, the larger the MTBF, the higher the reliability of the System. Reliability, $R(t)$, can be calculated, as

$$R(t) = \int_t^\infty \lambda \exp[-\lambda t]\,\mathrm{d}t$$

$$= \exp[-\lambda t]$$

There were only two machine faults which occurred such as controller defect and yaw sensor defect during the period of study. The failure rates of the controller and yaw sensor are 3.2×10^{-5}/h and 2.96×10^{-5}/h respectively. Since the components of the system are connected in series, the reliability factors of the components have been multiplied to find out the system reliability factors. It has been estimated that the system reliability will become zero at 85,000 h (Fig. 6) unless the failed components are repaired regularly.

The analysis for reliability improvement of the system has also been done. As indicated in Fig. 6, by removing 50% of controller defects the life time of the system can be improved from 85,000 h to 115,000 h. By removing yaw sensor defects completely the reliability of the system can be improved to have a life time of 165,000 h (Fig. 6). The failure rate is high in the case of controller defect and if it is removed completely, the life time of the system can still be improved to an extent of 180,000 h as shown in Fig. 6. The reliability factor of 0.5 at 10,000 h for wind energy system has been considered in the OREM model.

As a first approach to improving reliability, superior components and parts with low failure rates can be used. In order to design and develop a highly reliable component or unit, it requires a correspondingly high investment in the research and development activities. On the other hand, the cost of maintenance and spares would reduce with an increase in the reliability factor.

6. Distribution of renewable energy sources from OREM model

The OREM model gives the optimum allocation of renewable energy sources. It is found that at optimal condition, for lighting end-use, solar PV and biogas electricity conversion can be used to an extent of 0.5198×10^{15} KJ and 0.75×10^{15} KJ respectively (Fig. 7). The cooking end-use can be met by biomass direct combustion through

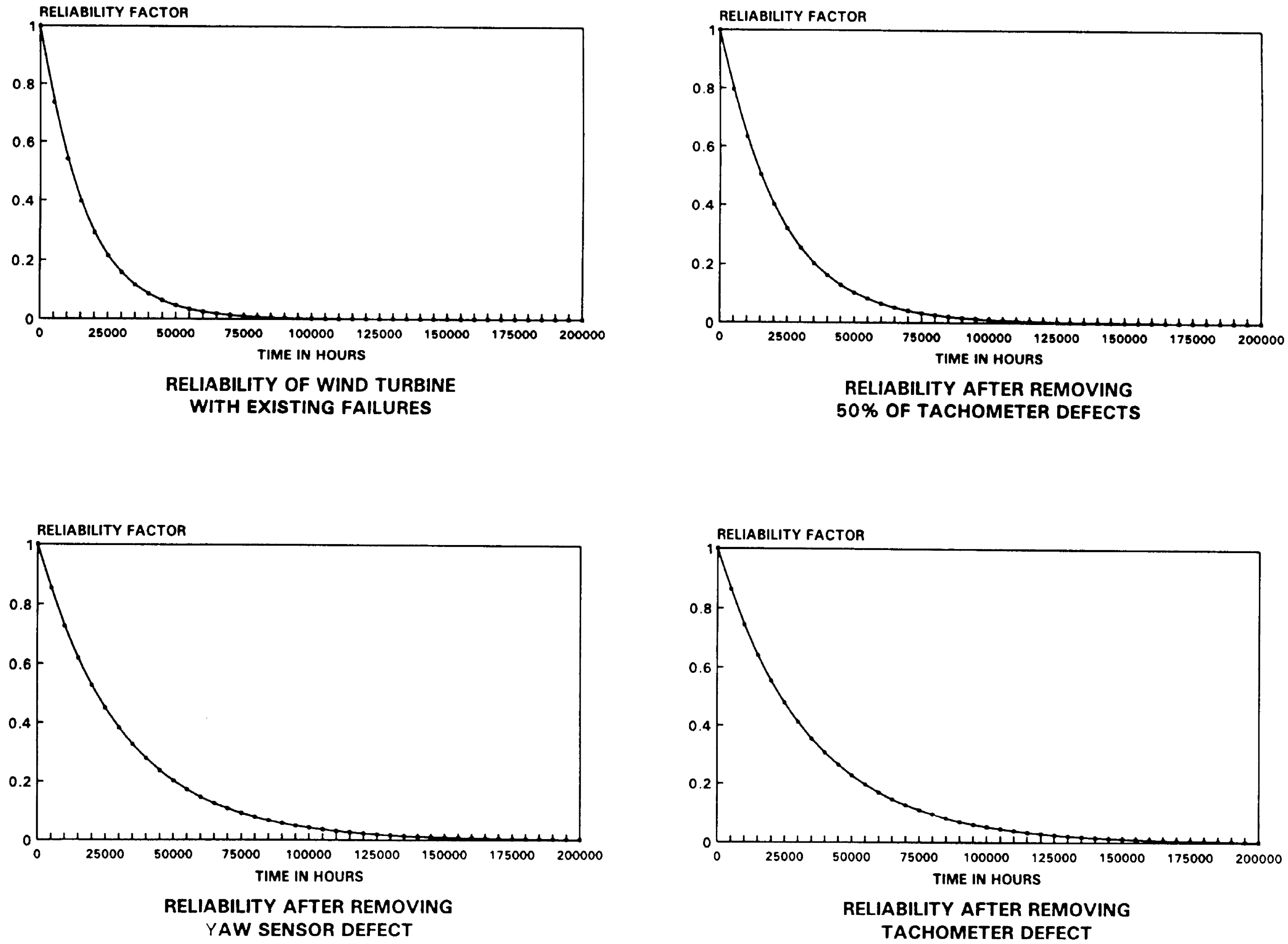

Fig. 6. Reliability factors of wind turbine generator.

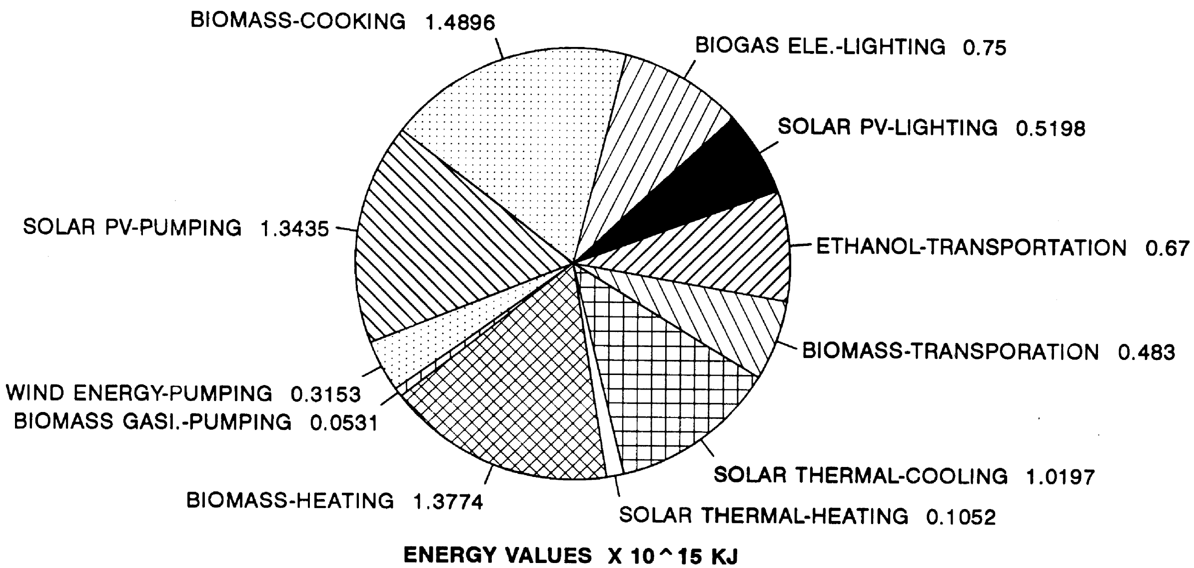

Fig. 7. Optimal renewable energy distribution pattern for the year 2020–21 in India.

improved chulas to an extent of 1.4896×10^{15} KJ. The pumping end-use can be shared by solar PV, wind energy and biomass gasifier to an extent of 1.3435×10^{15} KJ, 0.3153×10^{15} KJ and 0.0531×10^{15} KJ respectively. Solar thermal and biomass direct combustion can be used for heating to an extent of 0.1052×10^{15} KJ and 1.3774×10^{15} KJ respectively. The cooling end-use can be met by solar thermal to an extent of 1.0197×10^{15} KJ. The biomass gasifier and ethanol fueled engine can be utilised to an extent of 0.4830×10^{15} KJ and 0.67×10^{15} KJ respectively for transportation.

7. Effect of wind energy systems on optimal renewable energy model

The reliability factor for wind energy system is varied from 0.5 to 0.9 at 10,000 h. The optimum allocation of renewable energy is determined and shown in Fig. 8. When the reliability of wind energy system is improved the utilisation of wind energy in pumping end-use is also increasing proportionately. If the reliability factor is increased to 0.6 by minimising the component failures then the model selects the wind energy for pumping end-use to an extent of 0.5734×10^{15} KJ from 0.3153×10^{15} KJ, i.e. it increases by 19.79%. If the reliability factor is increased from 0.5 to 0.7 and 0.8 at 10,000 h the wind energy for pumping end-use increases by 39.86% and 60.03% respectively. There will be 82% increase in the utilisation of wind energy with the reliability factor of 0.9 at 10,000 h.

8. Conclusion

The average technical availability, real availability and capacity factor of the wind energy system are found to be 94.1%, 76.4% and 25.5% respectively.

Pareto analysis indicates that when grid failures are reduced by 50%, it resulted in an improvement of 33.1%, i.e., the frequency of grid failures can be reduced by 33.1%.

The average system down times due to inadequate wind speed is 18.8%. The average down time due to machine fault, machine maintenance, grid fault and gird maintenance are 0.8%, 0.2%, 3.3% and 0.6% respectively.

If the reliability factor is increased from 0.5 to 0.9 at 10,000 h by removing the controller and yaw sensor defects then the (OREM) model selects the wind energy for pumping end-use to an extent of 0.5734×10^{15} KJ from 0.3153×10^{15} KJ.

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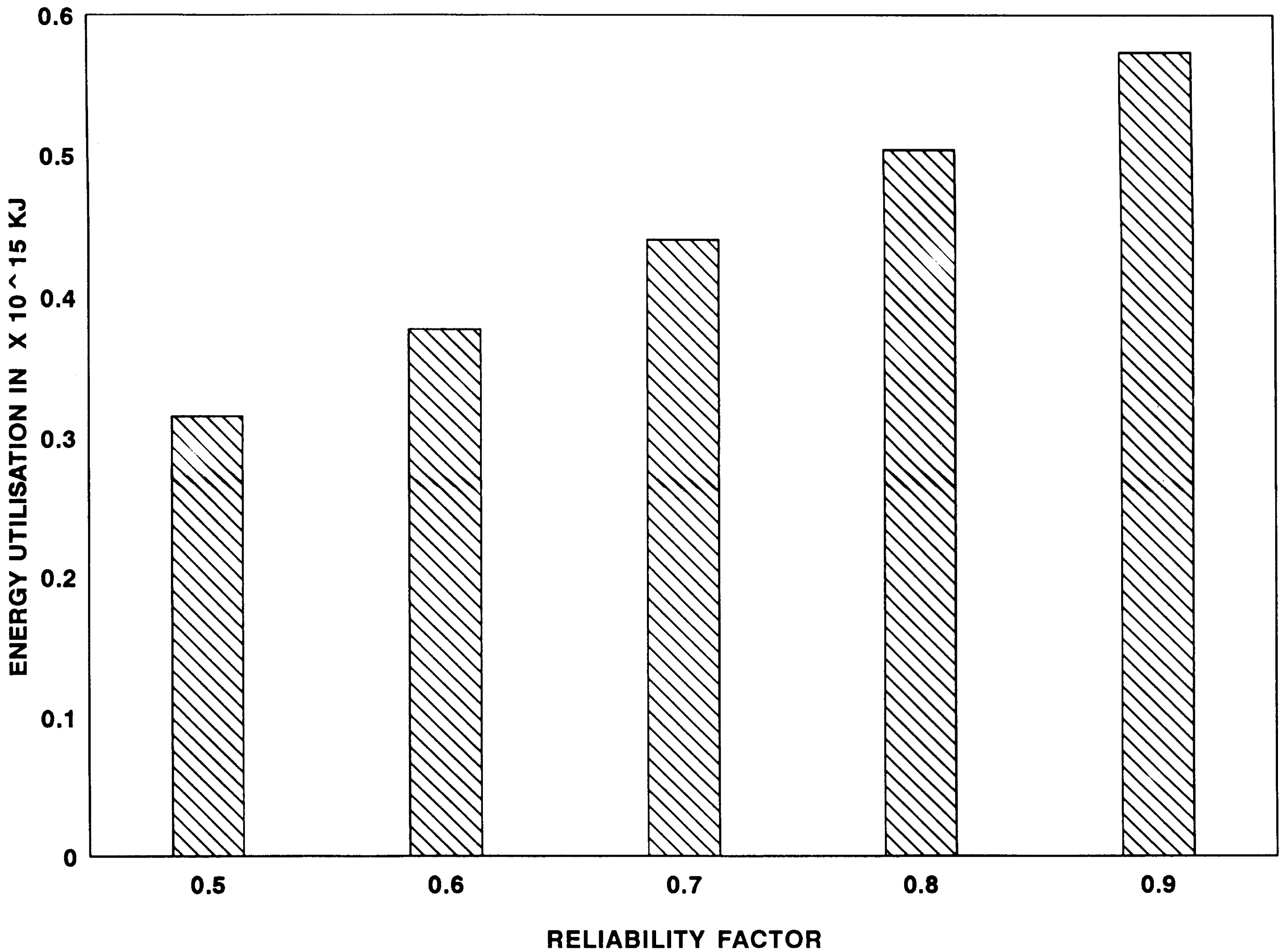

Fig. 8. Wind energy distribution pattern for pumping end-use at different reliability factor levels.

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